



## Verification of Collision Avoidance Functionality

A mileage multiplier approach to verify future Collision Avoidance Systems

*Master of Science Thesis in the Master Degree Programme Systems, Control and Mechatronics*

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Cover:

An example of what the Collision Avoidance System sees. Each square is a target found both by the radar and the camera. Both pedestrians and vehicles are identified.

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## SUMMARY

The report introduces a general method for verification of Collision Avoidance Systems. The method is based on a principle called *mileage multiplying*, consisting of nine steps. By using this method it might be possible to significantly reduce the need for data collection associated with the system verification. Targets, i.e. vehicles and pedestrians, are identified with aid from a radar and a camera. Information from these sensors are fused together by a sensor fusion algorithm. The system then determines if an intervention should be triggered.

It is relatively easy to verify that a Collision Avoidance System does an intervention when it should, but it is a much more complex task to conclude that the system will not make any so called unnecessary interventions. These unnecessary interventions might be annoying for the driver and should always be avoided. The mileage multiplier method consists of detecting interesting radar targets by analyzing collected traffic data. The radar targets are then modeled and inserted into the traffic data by using different statistical approaches. By simulating the Collision Avoidance Systems with the modified data as input, it is possible to analyze the system behavior to possibly find a measure of robustness for the specific situation. Data have been generated in a random fashion to better illustrate the strengths of the general method. The method should be used as a complement to conventional system verification. If a weakness of the Collision Avoidance System should be found, it is recommended to perform real life trials in order to validate the results.

Keywords: active safety, collision avoidance, mileage multiplier.



## **Acknowledgement**

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*Göteborg, May 2010*

*Niklas Augustsson*

*Martin Wilhelmsson*





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# 1. Introduction

This thesis presents a method to analyze the robustness of automotive *Collision Avoidance Systems* in general and Volvo's Collision Avoidance System in particular. A Collision Avoidance System is a safety system (described under chapter 2) which shall, in the future, contribute to the ambitious Volvo safety goal – no person should be seriously injured or die in a Volvo car by the year 2020 [1].

## 1.1. Vehicle Safety

Road crashes kill 1.2 million people worldwide every year and 50 million people are injured [2]. The more smart safety systems included in the car the greater the chance is to survive or even totally prevent an accident. Today it is important to build cars with efficient safety functions since customers in general demand a high safety level. Depending on their functionality, the safety systems are divided into *passive safety* and *active safety*.

### 1.1.1. Passive safety

Passive safety includes systems that mitigate the effects of an accident. One of the first passive safety systems was the seatbelt which prevent the driver and passengers from being tossed around or being ejected from the car. Advanced deformation zones of the car absorb a significant part of the collision energy during a crash which helps to mitigate the effects of an accident. Other commonly used examples of passive safety systems are airbags and advanced construction of the car structure itself. This design often results in dedicated collision impact zones or advanced safety solutions such as the Side Impact Protection System (SIPS), developed by Volvo. The SIPS system efficiently helps to absorb the kinetic energy of side collisions and thus enhances the safety for the occupants of the vehicle [3]. The development of passive safety systems has already reached very far which have resulted in an enormous reduction of traffic injuries and fatalities. However, every effort to increase the passive safety even further requires high costs for very small improvements [4]. Therefore the safety development today is mainly focused on active safety systems.

### 1.1.2. Active safety

Active safety includes systems that prevent accidents. To this category belong systems like *Anti-lock Braking Systems*, *Electronic Stability Control* and *Collision Avoidance Systems*. There is a general consensus that the future within vehicle safety lies within active safety systems. When it comes to development of Collision Avoidance, Volvo is already leading the way with advanced and innovative systems. Early systems had features like Lane Departure Warning (LDW) [5] and Forward Collision Warning (FCW) [6]. The more recent systems both have the ability of warning the driver when a collision is imminent and also, if possible, to autonomously brake the vehicle to avoid or mitigate an accident. Active safety systems are equipped with external sensors such as radar (Radio Detection and Ranging) and vision systems, which can supply the main system unit with information about the surrounding traffic.

## 1.2. Connection between Accidents and Velocity

It is a well known fact that vehicle speeds are of great importance when estimating the outcome of traffic accidents. According to the National Association for Traffic Safety Promotion (“Nationalföreningen för trafiksäkerhetens främjande”, NTF), an average speed reduction on rural highways with 10% could actually reduce the number of accidents with 20%. The same speed reduction could also lead to a reduction of personal injuries with 30% and the number of fatalities with nearly 40% [7]. This connection is clearly shown in Figure 1.

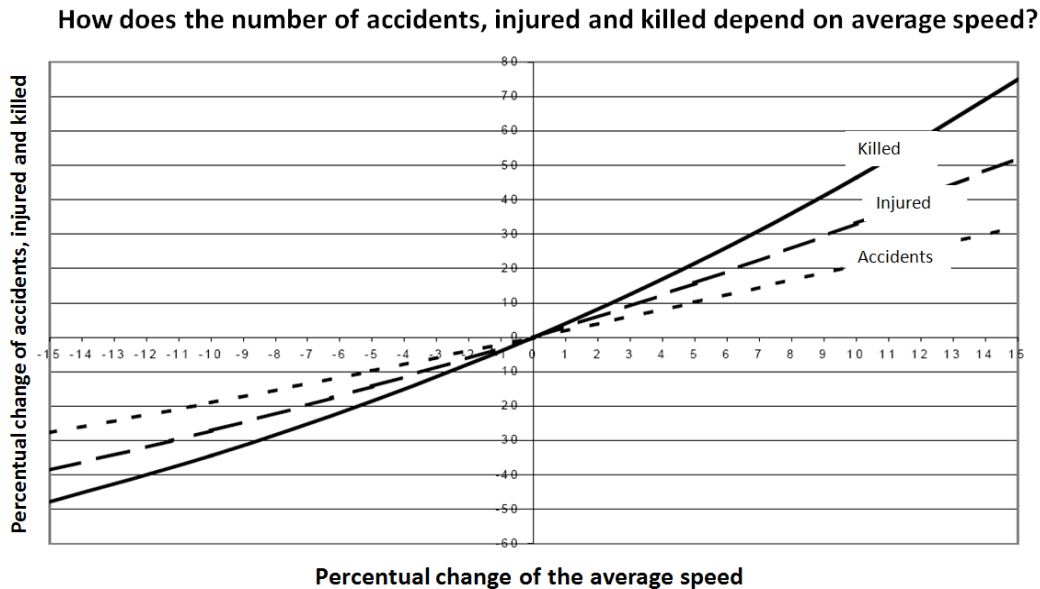
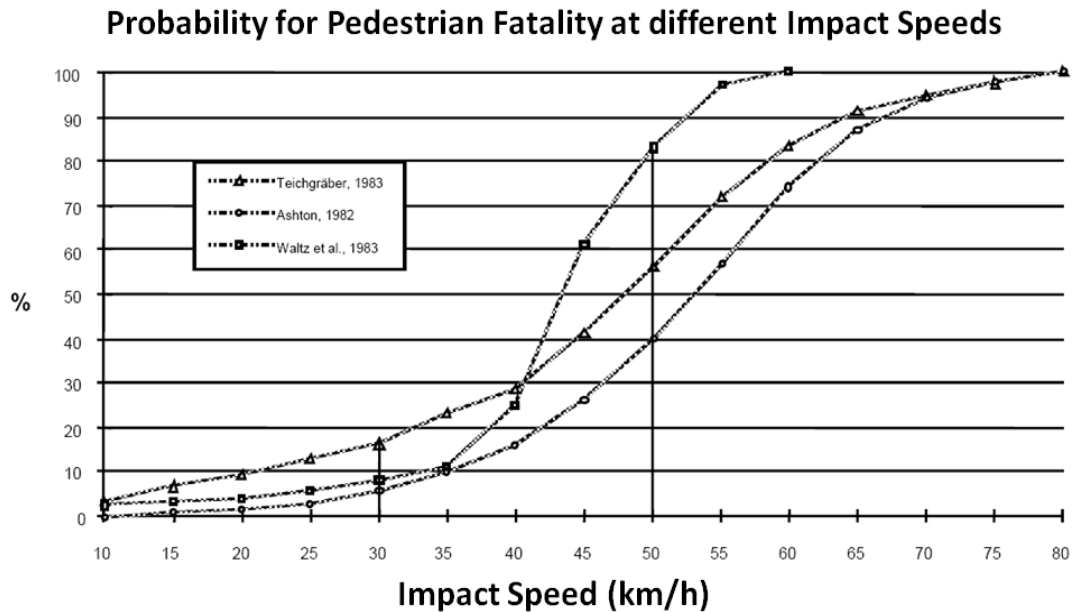


Figure 1 – How does the number of accidents, injured and killed depend on average speed? [7]

The figure describes the fact that velocity is very important to consider when analyzing traffic accidents and their effects. The average velocity level has a large impact on the collision speed, which in turn is very strongly connected to the fatality level of pedestrians during vehicle-pedestrian collisions. Due to the fact that the general pedestrian fatality level can be lowered significantly by reducing the impact speed, the need for active pedestrian detecting safety systems can be very strongly motivated. Of course, the reduction of impact speed that the active safety system performs will also have positive effects when considering vehicle to vehicle collisions. This is simply due to the fact that a lower impact speed implies a lower kinetic energy at the time of collision.



**Figure 2 – Probability for Pedestrian Fatality at different Impact Speeds**

The relation between the impact speed and the probability that a vehicle-pedestrian collision will have fatal outcome is described in Figure 2 [7]. The graph contains results from three real life studies of accidents between vehicles and pedestrians. The studies were performed during 1982-1983 and shows very similar results. As can be seen there is a very steep rise of pedestrian fatality between the speeds of 30 km/h up to about 50 km/h. The average fatality risk for pedestrians when the speed of impact is 30 km/h is only about 10%, while the fatality risk at an impact speed of 50 km/h lies between 40-80%. This implies that if active safety systems can help the driver to reduce the impact speed to or below about 30 km/h at the time of collision, several pedestrian lives could be saved.

It is important to remember that there are a lot of factors which might contribute to traffic accidents but the driver is always responsible for the safe operation of the vehicle. However, that does not mean that the driver necessarily is responsible for all accidents. Things might break, other people might crash into your vehicle, and there might be bad weather conditions and so on.

### 1.3. Problem description

It is of course important to verify that safety systems are working as intended. Therefore a lot of effort is spent to verify that everything works properly. Today, verification of Collision Avoidance Systems could for example be performed by analyzing thousands of driving hours or driving against dummy obstacles on specially dedicated test tracks. When changing hardware or including more functions into the Collision Avoidance System it is sometimes necessary to collect new data in order to verify these new functions. This is of course very cumbersome and not economically sustainable. These are two main reasons for developing more efficient verification methods.

### 1.4. Purpose

The purpose with the project is to find a method to reduce the verification time of Collision Avoidance Systems in general and Volvo's Collision Avoidance System in particular, by using the collected data in more efficient ways. This is performed by introducing a number of

additional and new powerful methods to analyze the data. By using a greater amount of the collected data the verification could be made more efficient and the time spent can be reduced significantly.

### **1.5. Objective**

The aim is to enable Volvo to rapidly introduce new, advanced and reliable safety systems to the market. Future and more complex active safety systems are likely to require more efficient methods in order to perform a verification which is as fast as or even faster than today. The new verification methods could efficiently reduce the development time and the total costs. Furthermore, an even more comprehensive system verification could be performed which might serve as an additional contribution to the verification of future advanced active safety systems.

### **1.6. Scope**

To verify that a safety system is braking when it should is relatively easy, since it is possible to provoke the system to intervene by driving against e.g. a dummy vehicle to check whether the car intervenes or not. However, to verify if the system makes an intervention when it actually should not is more difficult. These so called *unnecessary interventions* could be annoying for the driver and hence the focus of this project is aimed at unnecessary interventions.

### **1.7. Tools used**

Most of the work has been done with the aid from MATLAB and Simulink where a considerable amount of simulations and analysis work have been made.

## **PART I: System Description and Background Theory**

*In this section a System Description is given and fundamental theory is presented which is used in the method. The theory presented here will be referred to in the next section.*





## 2. General System Description

In this chapter a description of Active Safety and Collision Avoidance Systems in general is given. A summary describing some of the current available technologies as well as possible future systems is briefly presented. The goal is to put the Collision Avoidance System into a broader perspective. The functionality of these kinds of active safety systems is often based on some kind of forward looking sensor system.

### 2.1. Sensor and Communication Technology

In this section, important active safety sensor and communication technology is described. The sensors of active safety systems, which can be based on e.g. radar, laser or vision technology, generally provide information to a decision algorithm.

#### 2.1.1. Radar Technology

Radar technology is often used within active safety systems. The radar measurements can be used for example collision avoidance, distance warnings and within adaptive cruise control functions. The basics of radar technology are comprehensively described in for example [8] and [9]. Early radar sensors were often mechanically scanning. This means that the antenna is physically rotating or oscillating in order to cover the whole spectra. A more advanced and modern radar scanning approach is to use electronically scanning radar sensors. These radar sensors are comprised by an array containing multiple radar transceivers and can direct the radar beam with high accuracy by using phase modulation. This is basically carried out by introducing a short time delay between the different transceivers in the radar array. The properties of wave expansion will then create a concentrated radar beam of high energy through a phenomenon called interference. The basic functionality of the radar array beam direction is described in Figure 3 [10]. In the example in Figure 3, the time shifted input signals comes in from the left and into the radar array transceivers which sends radar pulses as soon as the input signal arrives to each transceiver. In the figure, some examples of resulting radar beams are shown.

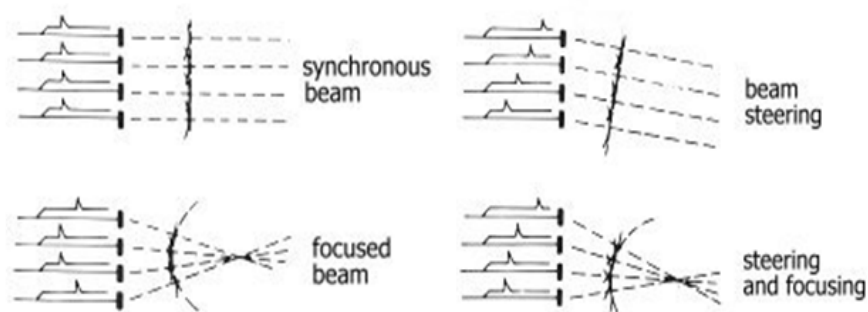


Figure 3 – Some examples of Radar Transmissions using Radar Arrays [10]

There are several nice advantages associated with the use of a radar array. One of the benefits is of course the possibility to control the radar beam very accurately and with high speed. The beam can easily be directed in any direction within the spectra, without the use of any mechanical parts. This implies that the radar sensor can be made very small and light weight which might enable easy mounting and implementation in the vehicle. If the electronically scanning radar is designed properly for the operating conditions it is intended to be working in, it might also have high safety of operation since all the eventual problems associated to the mechanics are eliminated.

The basic method used for detecting the range to a target when using pulse radar, can be described using the following formula which is often referred to as “*The Radar Formula*”

$$Distance\ to\ Target = \frac{\Delta t \cdot c}{2} \quad [eq. 1]$$

Here, the constant  $c$  represents the speed of light, which is

$$c = 299792458\ m/s \quad [eq. 2]$$

and  $\Delta t$  is the total signal travelling time from the transmission of the radar pulse until the reception of the radar pulse reflected by the target. The distance to the target can then easily be calculated by dividing the total travelling time by two. The same basic ranging principle can also be applied to other signals than radar, such as ultra sound ranging, laser or sonar signals in submarine applications. However, the speed constant must be adapted to the medium which the signal is travelling through, such as the speed of sound travelling through water.

Another commonly used radar principle is Continuous Wave (CW) transmission. This kind of radar does not use regular radar pulses but instead transmits a continuous signal, generally at a pre-specified frequency. By using this approach the CW radar enables easy measurements of the relative speed between the radar sensor and the reflecting target. This is done by simply analyzing the frequency shift of the received signal, occurring because of the so called Doppler Effect [11]. The received so called Doppler frequency  $f_D$  which is caused by a target object with a relative speed larger than zero can be written as

$$f_D = -2 * \lambda * v_{Relative} \quad [eq. 3]$$

where the wave length  $\lambda$  is described by

$$\lambda = \frac{c}{f} \quad [eq. 4]$$

and  $v_{Relative}$  is the relative speed between the radar sensor and the reflecting object. Since the received Doppler frequency  $f_D$  can be measured and the transmitted frequency  $f$  is already known, the relative speed to the target,  $v_{Relative}$ , can easily be calculated.

One disadvantage with standard CW transmission is that it is only possible to detect and track objects which have a relative speed larger than zero. The reason for this is that there will otherwise be no frequency shift at all in the received radar signal. However, there is a transmission method which enables detection of both speed and range to an object by using CW radar. By frequency modulating the transmitted CW signal it is possible to measure the time until the signal is received, and by using “*The Radar Formula*” [eq. 1] it is then possible to calculate the target range. The mentioned radar theories are thoroughly described in [8] and [9].

### 2.1.2. Vision Technology

Many active safety systems use vision sensors for assessing the traffic situation. Image processing is commonly used to identify different objects, such as vehicles and pedestrians [12]. By using the vision sensor together with another and complementing sensor system, such as radar, beneficial synergetic effects can be gained. For example, a radar sensor might provide the active safety system with an accurate range measurement to an object. The vision system could then provide an accurate angular position of the object as well as a classification e.g. as a pedestrian, a car or a motorcycle.

### 2.1.3. CAN Technology

Many vehicle systems use a Controller Area Network (CAN) serial communication bus for data transmission. The CAN protocol, which was introduced by Robert Bosch GmbH in 1986, is commonly used in vehicle systems since it is beneficial to use for connecting sensors and system modules within a relatively short transmitting distance. According to Robert Bosch GmbH, the maximum transmission rate is specified to 1 Mbit/s which applies for networks with transmitting distances up to 40 m [13]. Although originally being developed for the automotive industry the CAN bus is also increasingly used for other applications such as within industrial field bus systems. Some of the main benefits with using a CAN serial bus are a low cost, a high ability to function in difficult electrical environments, efficient error detection and real time capability, as well as user friendliness. Due to its high reliability level the CAN protocol is suitable for systems with high reliability requirements, such as for active safety systems. [13]

## 2.2. Active Safety Systems

The future within development of vehicle safety systems is mainly considered to be within active safety. Today, there are already several extremely clever solutions available on the market with the aim of increasing the safety for both the driver and passengers as well as for the surrounding traffic and pedestrians. The common factor for these systems is that they continuously use some kind of sensor technology and electronics to survey and assess the traffic situation or the state of the vehicle. The systems also have the capacity to decide if some kind of action is needed in order to avoid potential risk situations. This action can for example consist in warning or informing the driver. Other possible interventions from the systems can be to pre-charge or fully activate the brakes in order to avoid or mitigate the effects of an accident. The basic conceptual functions of all active safety systems can be described using three so called layers, consisting of:

- *Perception Layer*
- *Decision Layer*
- *Action Layer*

These three layers are further described in [14] and in [15]. The *Perception Layer* collects and handles information about the traffic environment by using different sensors. The sensors can use for example radar, laser or vision technology. The *Perception Layer* also has an important task of providing information to the so called *Decision Layer*. In this layer a decision is made whether the system should trigger an intervention or not. The final layer which is called the *Action Layer* is used to activate any action or to provide the driver with important information. The aim is to design the human to machine interface (HMI) to enable as efficient information transfer from the system to the driver as possible. The safety system

design can be enhanced by using knowledge about driver behavior as well as human to machine interaction.

### 2.2.1. Collision Mitigation Systems

Some systems are designed to mitigate the effects of already occurring traffic accidents for example by reducing the impact speed or inflating an external airbag. Other possible actions can be to stretch the safety belts or closing the car windows and sunroof prior to an upcoming collision. The system might also perform a pre-charge of the brake system or activate a full auto brake. The braking pre-charge functionality can provide the driver with very rapid activation of full braking power when he or she initiates an emergency brake. The Collision Mitigation Systems (CMS) can significantly reduce the effects of a collision which makes them a very important part of active safety systems today. It has also been investigated and shown that the amount of collisions between vehicles and pedestrians with fatal outcome can be significantly reduced if the impact speed is lowered below a certain level [8]. This is clearly shown in Figure 2. For that purpose, as well as when considering vehicle to vehicle collisions, the collision mitigation systems can play a very important role in reducing the number of injuries and fatalities.

### 2.2.2. Forward Collision Warning

The active safety functions used for Forward Collision Warning are of course very useful since they might help to notify distracted drivers about upcoming threats ahead of the vehicle. According to an analysis of American rear end collisions the driver remained passive before the collision in over 78% of the crashes [16]. There has also been research of the preliminary safety benefits which shows that a Forward Collision Warning system have the possibility of preventing 51% of the rear end collisions reported by the police in the United States [17]. Therefore it is evident that Forward Collision Warning systems are very important for the total vehicle safety level. The decision algorithm within the Forward Collision Warning estimate the threat for each situation and can if necessary warn the driver by activating warning signals visually or audially. These kinds of active safety systems normally use some sort of Human Machine Interface (HMI) to call for attention from the driver. One example of a visual warning signal is shown in Figure 4. A red light beam is being projected onto the windscreen by an array of LEDs (Light Emitting Diode), mimicking the brake lights of a vehicle ahead. When the red visual warning signal is lit up, an audial warning is activated.



Figure 4 – Forward Collision Warning – Visual warning activated.

### 2.2.3. Lane Departure Warning

Since it is a crucial factor for traffic safety to maintain a safe position within the driving lane as well as keeping a safe distance between vehicles at all times, the functionality of a Lane Departure Warning (LDW) system proves to be very useful. According to [18], Single Vehicle Road Departure (SVRD) accidents correspond to about 20% of the traffic accidents and up to around 40% of the fatalities in total. The basic function of LDW systems is to warn the driver when the vehicle is unintentionally leaving the current driving lane, as shown in Figure 5.

Many modern LDW systems make use of a forward looking vision system to indicate the boundaries of the traffic lanes. In general the systems will process the vision information to find linear patterns, such as lane markings or the outer boundary of the road. This could for example be done using edge detection. Of course detection of linear edges such as painted lane markings is associated with some difficulties which pose high demands on the designers. As an example, the system needs to have the ability to handle many different types of lane markings, which naturally can be designed in numerous ways. Another factor which has to be considered is varying light conditions. The vision system needs to be robust for many different traffic environments at all possible light conditions. An interesting special case which can be seen as a challenge for the system is for example when entering or leaving a road tunnel. At this situation the lighting conditions change significantly in a very short time. The challenges of this special case are described in [19]. Moreover, the reference points used by the Lane Departure Warning system could also at some points become hidden by other vehicles which might set demands for the system to track and forecast the lane curvature based on previous and historical input data. An interesting possibility which is currently investigated by system manufacturers is to add the functionality of a rear facing camera to provide enhanced robustness for example when the forward facing camera is blinded by heavy sun light. [20]



Figure 5 – Lane Departure Warning

### 2.2.4. Lane Change Aid

When a lane change is performed it always implicates a certain amount of risk. If a vehicle in a neighboring lane is concurrently approaching from the rear it might sometimes be hard for the first driver to detect the nearby approaching vehicle. This might be due to the phenomenon of blind spots but it could also originate in driver inattention [21]. The functionality of Lane Change Aid systems are based on sensors which indicate the presence of a nearby vehicle in the blind spot of a neighboring lane, as shown in Figure 6. The types of in-vehicle sensors which are used might vary from system to system but Radar, Lidar<sup>1</sup> (Light Detection and Ranging) and Vision are all proposed methods in technical literature. All of these solutions are considered to be very useful for implementation. There are several car manufacturers who provide Lane Change Aiding systems; one of them is Volvo that introduced the BLIS (Blind Spot Information System) in 2004. BLIS detects vehicles appearing in the blind spot using sensors mounted in the side rear view mirrors. The BLIS notifies the driver when a vehicle is currently in the blind spot area by lighting up a signal mounted in the interior close to the side rear view mirror.

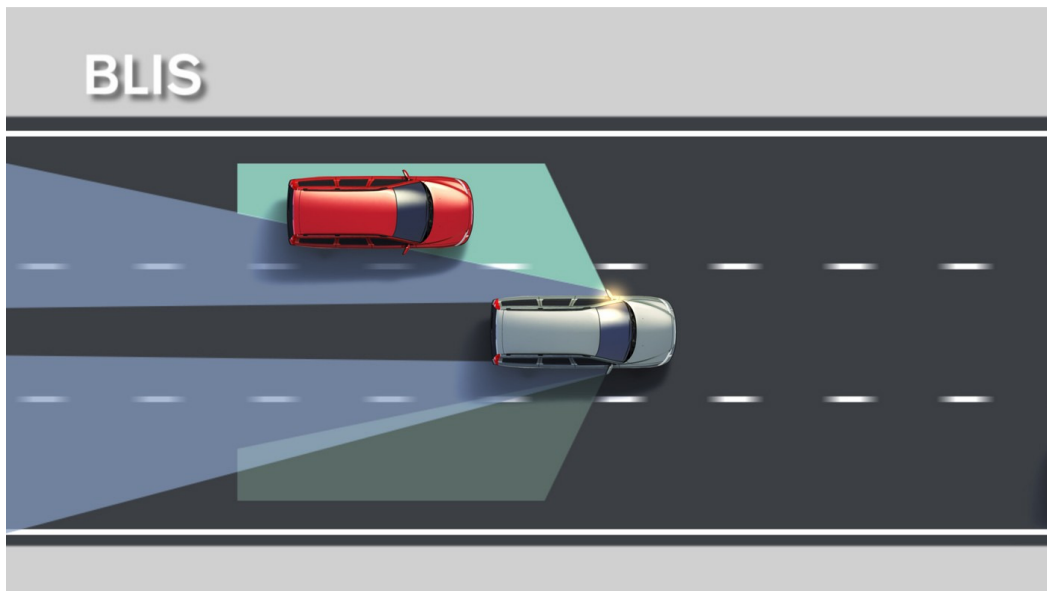


Figure 6 – Blind Spot Information System

### 2.2.5. Adaptive Cruise Control

The future within cruise control systems development is likely to be aimed towards adaptive systems. Adaptive cruise control systems can autonomously control the range between the host vehicle and the vehicle ahead of the ego vehicle. When the road ahead is clear the system automatically adjusts the velocity up to the user defined level. These kinds of systems can be very useful for maintaining a safe distance to the closest vehicle ahead and enable the driver to concentrate on other important aspects of driving. It is common that the user has the ability of controlling the system by specifying a preferred distance up to the closest vehicle ahead, as well as a preferred speed level when the road is clear.

Advanced adaptive cruise control systems can contain functions such as queue assist, where the ACC equipped vehicle automatically follows the vehicle ahead from stand still and up to

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<sup>1</sup> Lidar technology (Light Detection and Ranging) uses the exact same principle as Radar but with laser instead of radio signals.

a specific speed level. This kind of function can for example be found within the ACC system available for the new Volvo S60 [22].

### 2.2.6. Vehicle to Vehicle Communication

The area of communication between vehicles provides interesting possibilities for developing new and advanced safety features. This field of vehicle development has received a lot of attention lately since it has potential of taking vehicle safety a significant step forward. By using wireless communication equipment as a complement to existing active safety system it is possible to forward important information, such as slippery conditions, to other concerned vehicles.

### 2.3. Collision Avoidance Systems Overview

Systems with full ability of avoiding a collision by activating a brake action or by performing an evasive steering maneuver are called Collision Avoidance Systems (CAS). An important aspect of these systems is that they could prevent accidents from occurring at all by performing an early intervention. The general functionality of Collision Avoidance Systems has large similarities with the Collision Mitigation Systems, described under 2.2.1. The significant difference between CMS and CAS is that the latter is authorized to activate evasive actions at an earlier stage compared to the CMS. Early brake intervention is needed in order for the CAS to totally avoid the accident. Efficient and reliable threat assessment algorithms are important for both CMS and CAS. However, collision avoidance systems might require higher demands on quick and reliable threat assessment compared to collision mitigation systems. This is because the decision to trigger an intervention is generally performed much earlier when using a CAS.

A schematic example of how a CAS could be designed is shown in Figure 7. As can be seen, the CAS uses information from several sensors. In this case, the CAS is designed using mainly radar and vision data as input. Additional information is supplied to the CAS by other sensors which can provide the system with important information about the state of the vehicle such as speed, yaw rate and acceleration.

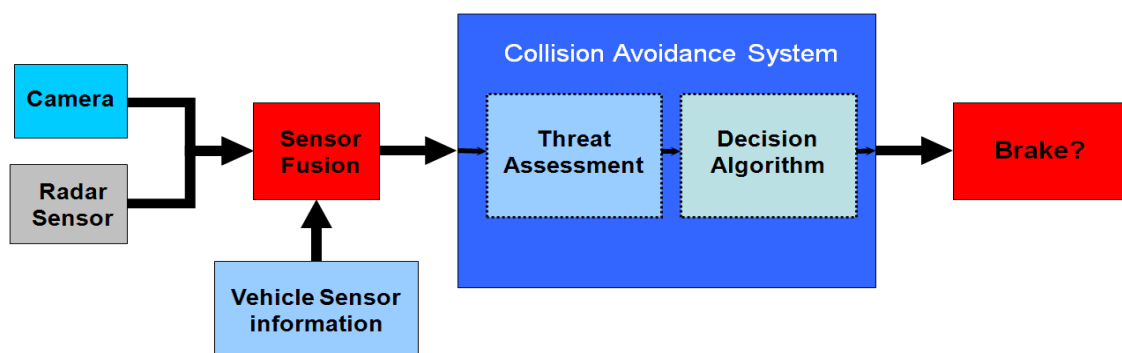


Figure 7 – Functional Overview of a Collision Avoidance System

In this example, the radar data is processed together with the vision data in a sensor fusion algorithm where information from the two sensors is fused into confirmed target tracks. There is a wide area of technical publications handling sensor fusion, such as [23]. Sensor

fusion is a separate and complex topic; this implies that a target matching algorithm could be designed in numerous ways.

However, for this particular system example, the requirements in order for the sensor fusion algorithm to fuse the data into a fused target track are that the target has to be confirmed by both the vision and the radar system. Hence, if an object is seen by both radar and vision, a fused target track is created. The fused target tracks are sent into the CAS together with the additional information from the vehicle sensors described above. In this simplified example the CAS functionality is described by two main processes, namely the Threat Assessment (TA) and the Decision Algorithm (DA). These two processes are very important for the CAS functionality.

The TA is an advanced process, whose functionality can vary depending on the system design. The TA algorithm generally provides the DA with a threat level which is used to make decisions whether to trigger a brake intervention or not, based on the input information from the TA algorithm.

In order to evaluate the threat level of a specific situation, some parameters are commonly used by Collision Avoidance Systems. These parameters are described under 2.3.1. It is however important to note that this is only an example of how the threat assessment problem can be solved. There are several methods available for estimating the current threat level of a specific traffic situation, such as the method described in [24].

### **2.3.1. Threat assessment**

As an example of how Collision Avoidance Systems estimate the general threat level of a specific situation, some important key values could be used. These parameters, which are commonly used by CAS are briefly described in this section. As mentioned there are other existing TA solutions as well. One alternative example where the threat assessment is based on another measure, called ‘time-to-last-second-braking’ is presented in [24].

#### **2.3.1.1. Braking threat number**

The Braking Threat Number (BTN), or parameters similar to BTN, is often a very important parameter for active collision mitigation and avoidance systems. The CAS described in this thesis uses BTN and Steering Threat Number (STN, described under 2.3.1.2) as key variables to determine the threat level of a traffic situation. The BTN is defined as the ratio between the required deceleration level (requested braking capacity) and the maximum available estimated deceleration level (available braking capacity).

$$BTN = \frac{a_{required}}{\tilde{a}_{maximum}} \quad [\text{eq. 5}]$$

This implies that when BTN is equal to or lower than one, it is possible for the car to stop before a collision occurs, assumed that the estimated deceleration level is correct. However, if the BTN level is above one, a collision can no longer be avoided solely by braking. The value of  $\tilde{a}_{maximum}$  describes the current maximum achievable value of acceleration during a braking maneuver of the host vehicle [25].

#### **2.3.1.2. Steering threat number**

Together with the BTN, the value of the Steering Threat Number (STN) has a key role in evaluating a traffic threat situation. The STN is defined as the ratio between the requested



lateral acceleration and the maximum available estimated lateral acceleration [25]. In other words this can be described as the requested steering action divided by the maximum steering action available.

$$STN = \frac{a_{required,lateral}}{a_{maximum,lateral}} \quad [\text{eq. 6}]$$

As with the case of BTN, when the STN level is equal to or above one it is no longer possible to avoid a collision solely by performing a steering maneuver.



### 3. Overview of the developed method

This chapter gives an overview of the developed method for the verification. The method is called *mileage multiplier* and the meaning of this will be explained in this section. In addition, an overview of all the steps included to develop the method is presented to give the reader a better understanding of the rest of the report.

The fundamental idea behind mileage multiplying is to place targets in an already existing environment thus creating more important traffic situations. This technique can potentially lead to a reduction of the need for traffic data collection. The verification time could also potentially be shortened. As an example, let's say that a certain potential dangerous situation is found once every kilometer. By virtually placing such targets, say 100 times, during one of these kilometers, it is possible to claim that the host vehicle has driven 100 km instead of the actual 1 km (over this particular situation). The method consists of a number of steps shown in Figure 8. The nine method steps are listed in 3.1 where the purpose and goal of each step is shortly described. Modeling is performed in steps one to four while step five to eight mainly consists of evaluation of performance.

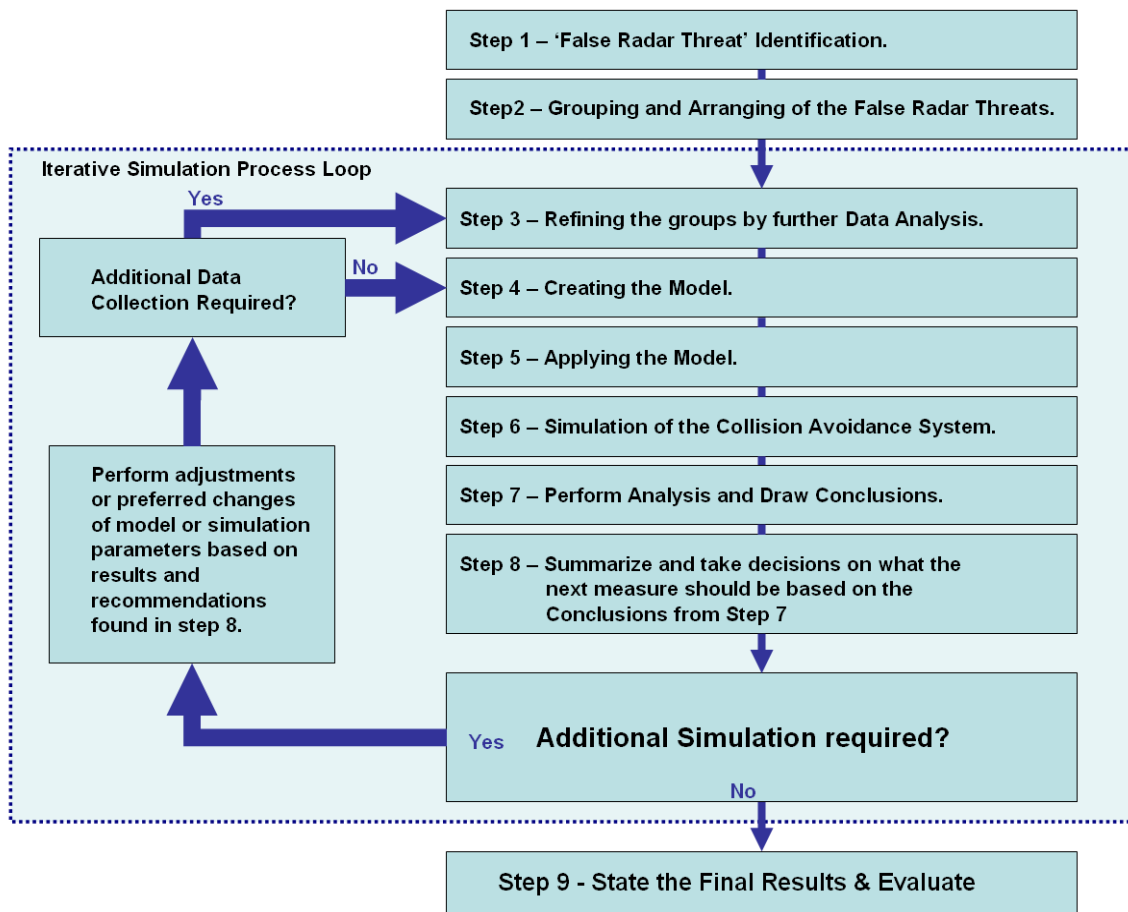


Figure 8 – Mileage Multiplier Method Flow Chart

### 3.1. Short Method Step Description

A short description of the nine method steps is given below. More detailed step information can be found under the section *The Mileage Multiplier – Step by Step Description* in Chapter 2.

- **Step 1 – False Radar Threat Identification.** This step of the method consists in determining the possibly weak spots of the radar system. *When, Why and How often* is the radar finding possibly false threats? These are important questions to be answered.
- **Step 2 – Grouping and Arranging of the false Radar Threats.** During this step the task is to create rough mathematical models of all false radar threats found from *Step 1*. This will result in a number of different target groups.
- **Step 3 – Refining the groups by further Data Analysis.** Use the arranged groups from *Step 2* and analyze extensive data about each specific threat. Data such as detection range, reflection power and width of target are deeply analyzed and stored.
- **Step 4 – Creating the Models.** In this step a radar model for each target set is created based on e.g. the statistical properties from the data collected in *Step 3*.
- **Step 5 – Apply the Model.** It is now time to insert the modeled radar targets into the system and thus creating the new modified traffic data. This can be done in a variety of ways using different approaches depending on what the aim of the simulation is. It is recommended and very useful to decide at an early stage what the objective with the simulation should be, in order to make the verification work as efficient and structured as possible.
- **Step 6 – Simulation of the Collision Avoidance System.** Perform the planned simulations and log the results as well as every possible important parameter carefully in order to enable comprehensive analysis at a later stage.
- **Step 7 – Perform Analysis and Draw Conclusions.** Analyze all results carefully and draw conclusions. Has the system applied the brakes? Can any interesting behavior be found? *Where, Why and How often* are important questions to consider.
- **Step 8 – Summarize and Take Decisions.** At this step the simulation results are summarized and decisions for the work progress should be made based on the experiences from the earlier steps. At this point it is useful to consider what the next step should be? A new simulation with some modified parameters? A natural progress loop consists in iterating *Step 4* to *Step 8* until a satisfying result is achieved.
- **Step 9 – State Final Results and Evaluate.** When a satisfying result from the process is achieved it could be advantageous to state what the final conclusions are – Have the system fulfilled the specified requirements? Do any improvements have to be made? It is also very important to evaluate if the method approach could be rationalized in any way, based on experiences gained during the total process.

## 4. Theory

In this section background theory is presented which is used in the method. The theory here will be referred to in the next section.

### 4.1. Host vehicle model

There are many ways to model the movement of a car. One common way is to use a bicycle model [14], but here a simplified model will be derived. This model will work fine with the application it is intended to be used for. All parameters in this derivation are defined in Figure 9.

First, a global coordinate frame  $(x, y)$  is defined and placed in the front bumper of the host vehicle at the first sample. In addition, a local coordinate frame is placed in the front bumper of the host vehicle and this system translates and rotates with the car. By defining the position of the host vehicle in the global coordinate frame as  $(x_{host}, y_{host})$  and a position in the local coordinate system as  $(x', y')$ , the same position in the global system is expressed as (see e.g. [25] for more information about rotation matrices)

$$\begin{cases} x = x_{host} + x' \cdot \cos(\psi) - y' \cdot \sin(\psi) \\ y = y_{host} + x' \cdot \sin(\psi) + y' \cdot \cos(\psi) \end{cases} \quad [\text{eq. 7}]$$

where  $\psi$  is the rotation of the local coordinate frame, i.e. the rotation of the host vehicle. This angle is called the yaw angle. The yaw angle is not available from sensor information and consequently this angle has to be derived. By assuming that the yaw rate,  $\dot{\psi}$ , is constant between two consecutive samples and if the yaw angle is defined to be zero at the first sample,  $\psi$  can be derived by solving the recursive equation

$$\begin{cases} \psi^{k+1} = \psi^k + \dot{\psi}^k \cdot \Delta t \\ \psi^1 = 0 \end{cases} \quad [\text{eq. 8}]$$

Here  $\Delta t$  is the sample time and the superscript,  $k$ , denotes the sample number. Moreover, by assuming that the host vehicle is driving along a straight line (i.e no curvilinear movement) during the sample time, the distance the host vehicle is moving between two samples,  $d_{travel}^k$ , is estimated according to

$$d_{travel}^k = \max(0, v_{host}^k \cdot \Delta t + a_{host}^k \cdot \frac{\Delta t^2}{2}) \quad [\text{eq. 9}]$$

where  $v_{host}$  is the speed of the host vehicle,  $a_{host}$  is the acceleration of the host vehicle and  $\Delta t$  is the sample time. The max function assures that  $d_{travel}^k$  is non-negative. With this information it is now possible to derive the longitudinal and lateral movement,  $d_{long}$  and  $d_{lat}$  respectively, according to

$$\begin{cases} d_{long}^k = \cos(\psi^k) \cdot d_{travel}^k \\ d_{lat}^k = \sin(\psi^k) \cdot d_{travel}^k \end{cases} \quad [\text{eq. 10}]$$

Since the global coordinate frame is placed at the front bumper of the vehicle at sample number one (i.e. the first time the radar sees the target) the position of the host vehicle is then derived by solving this recursive equation

$$\begin{cases} x_{host}^{k+1} = d_{long}^k + x_{host}^k \\ y_{host}^{k+1} = d_{lat}^k + y_{host}^k \\ x_{host}^1 = 0 \\ y_{host}^1 = 0 \end{cases} \quad [\text{eq. 11}]$$

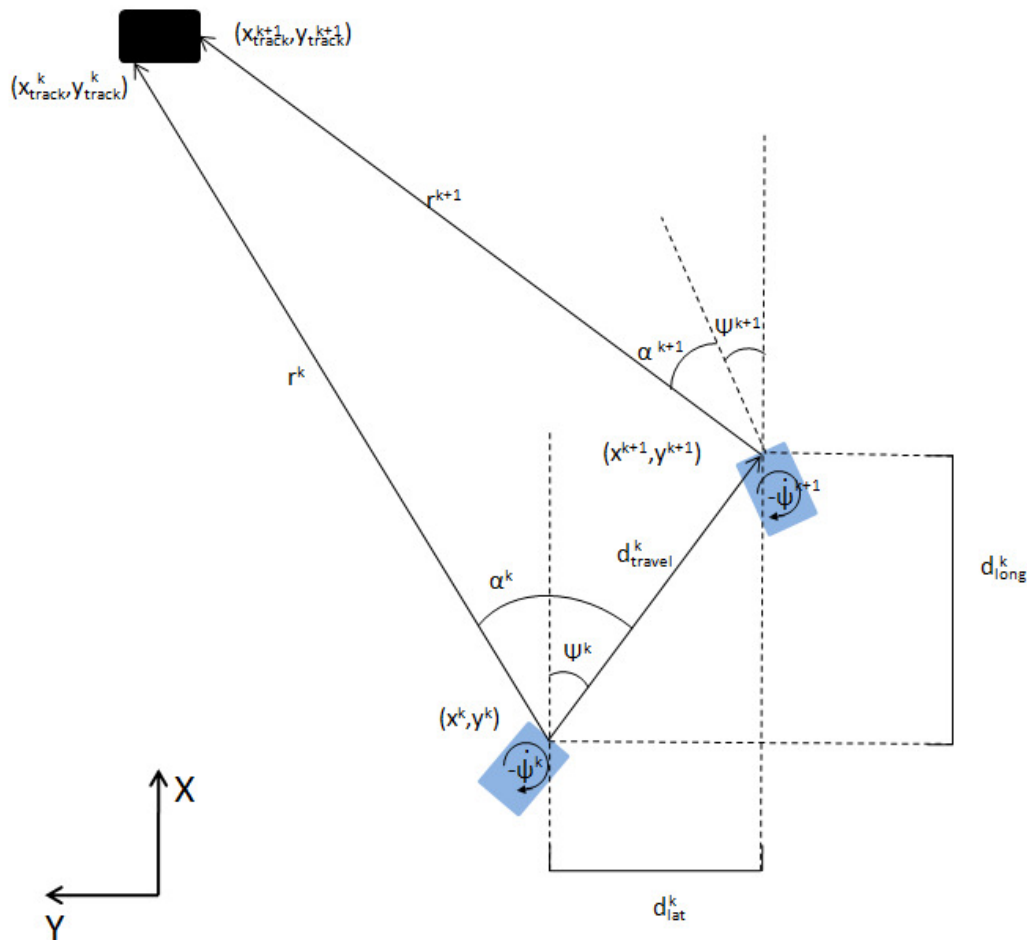


Figure 9 – Definition of the variables used in the host vehicle model

## 4.2. Stationary target model

Even though a stationary radar target doesn't move, the radar reflections might not be static. This is due to the fact that the reflection can come from different places of the target. For example, the radar reflection of a well in the road can first come from the front of the well and in the next sample from the back, thus giving the impression that the target has moved itself. To be able to model the radar reflection movement (i.e. the tracks, see Figure 9), a statistical foundation needs to be created. How much does the radar hit move in general? To be able to answer this question a number of derivations has to be carried out. To determine the movement of the target, what is needed is to derive where the tracks

are situated in the global coordinate system. The angle and range to the target,  $\alpha$  and  $r$  respectively, are available via sensors and this information can easily be converted to Cartesian coordinates according to

$$\begin{cases} x'^k = \sin(\alpha^k) \cdot r^k \\ y'^k = \cos(\alpha^k) \cdot r^k \end{cases} \quad [\text{eq. 12}]$$

These coordinates can then be converted into global coordinates by using [eq. 7]. A simple model to estimate the position of the target is to assume that the target position is in the mean position of the tracks, i.e.

$$\begin{cases} x = \frac{1}{k} \sum_k x_{track}^k \\ y = \frac{1}{k} \sum_k y_{track}^k \end{cases} \quad [\text{eq. 13}]$$

The variance of the tracks from this mean position,  $s^2$ , can be computed according to

$$\begin{cases} s_x^2 = \frac{\sum_k (x_{track}^k - x)^2}{N-1} \\ s_y^2 = \frac{\sum_k (y_{track}^k - y)^2}{N-1} \end{cases} \quad [\text{eq. 14}]$$

where  $N$  is the total number of tracks.

### 4.3. From global to local coordinate frame

A stationary target does not move in a global coordinate frame. In a local coordinate frame, however, the coordinates will change. The relationship can be derived from [eq. 7],

$$\begin{cases} x' = -x_{host} + x \cdot \cos(-\psi) - y \cdot \sin(-\psi) \\ y' = -y_{host} + y \cdot \sin(-\psi) + x \cdot \cos(-\psi) \end{cases} \quad [\text{eq. 15}]$$

These coordinates can then be converted into polar form,

$$\begin{cases} r = \sqrt{x'^2 + y'^2} \\ \alpha = \tan^{-1} \left( \frac{y'}{x'} \right) \end{cases} \quad [\text{eq. 16}]$$

### 4.4. Random variables: Fundamental theory

In this section fundamental facts behind random variables used later in the thesis will be presented. More information and proofs to some of the facts presented here and in the next chapter about simulation techniques can be found in e.g. [27].

#### 4.4.1. Expected value

The expected value, or mean, of a discrete random variable  $X$  is denoted  $E[X]$  or  $\mu$  and is defined as

$$E[X] = \mu = \sum_i x_i \cdot p(x_i) \quad [\text{eq. 17}]$$

where  $p(x_i)$  is the probability that  $X$  will take the value  $x_i$ .

#### 4.4.2. Variance

The variance of a random variable is a measure of how much the random variable varies around its mean value. It is denoted  $Var[X]$  or  $\sigma^2$  and defined as

$$Var[X] = \sigma^2 = E[(X - \mu)^2] \quad [\text{eq. 18}]$$

#### 4.4.3. Covariance and correlation

The covariance and correlation measures the linear relation between two variables. The covariance between two random variables,  $X$  and  $Y$ , is defined as

$$Cov[X, Y] = E[(X - E[X]) \cdot (Y - E[Y])] \quad [\text{eq. 19}]$$

The correlation,  $\rho$ , can take values between -1 and 1 and is simply a normalization of the covariance

$$\rho = \frac{Cov[X, Y]}{\sqrt{\sigma_X^2 \cdot \sigma_Y^2}} \quad [\text{eq. 20}]$$

#### 4.4.4. Bernoulli process

A Bernoulli process is a sequence of independent random variables  $(X_1, X_2, \dots)$  such that for each  $i$  the value of  $X_i$  is either 0 or 1 and the probability that  $X_i = 1$  is the same for all  $i$ .

#### 4.4.5. Conditional probability

Conditional probability is the probability of some event  $A$ , given the occurrence of some other event  $B$ . The probability that event  $A$  occurs given the event  $B$  is denoted

$$P(A|B)$$

A well known formula is Bayes' theorem which says

$$P(A|B) = P(B|A) \cdot \frac{P(A)}{P(B)} \quad [\text{eq. 21}]$$

### 4.5. Random variables: Simulation techniques

This chapter describes how to generate and simulate random variables. First a description of how to generate correlated random variables will be given. Then, a description of how to generate random numbers from a Gaussian distribution will be described. Lastly, techniques to simulate rare events are presented.

#### 4.5.1. Generation of correlated random variables

Generally it is of interest to generate random variables with a correct distribution and correct correlation characteristics. How this is done will be presented in this section, both in the one dimension case and also in the multiple dimension case.

##### 4.5.1.1. One dimension

From the collected data, the correlation coefficient  $\rho_m$  between two variables (let's call them  $X_m$  and  $Y_m$ ) is first derived. To recreate this relation between the two variables, set e.g.



$$X = aY_m + Z \quad [\text{eq. 22}]$$

where  $X$  is the new variable which should have the same correlation with  $Y_m$  as  $X_m$  and the same distribution as  $X_m$ ,  $a$  is some constant and  $Z$  is a random variable uncorrelated with  $Y_m$ . Since we want the correlation between  $X$  and  $Y_m$  to be  $\rho_m$  the constant  $a$  and the statistical properties of  $Z$  must be determined. The mean (or expected value) of  $X$  is equal to

$$E[X] = aE[Y_m] + E[Z]$$

and hence, the expected value of  $Z$  becomes

$$E[Z] = E[X_m] - a \cdot E[Y_m]$$

Similarly, the variance of  $Z$  is derived according to

$$\text{Var}(X) = \text{Var}(aY + Z) = a^2\text{Var}(Y) + \text{Var}(Z) + 2\text{Cov}(Y, Z) = a^2\text{Var}(Y) + \text{Var}(Z)$$

and hence

$$\text{Var}(Z) = \text{Var}(X_m) - a^2\text{Var}(Y_m)$$

If one is lucky this distribution of  $Z$  is (approximately) Gaussian and consequently the only parameters needed is the mean and the variance. In reality the distribution could be much more complex, and thus it might be difficult to find an analytical expression. Instead, a numerical approximation could be to prefer in such case.

Now to the constant  $a$ . The correlation between two random variables  $X$  and  $Y$  was defined in [eq. 20]. The covariance is in this case

$$\text{Cov}(X, Y_m) = \text{Cov}(a \cdot Y_m + Z, Y_m) = a \cdot \text{Cov}(Y_m, Y_m) + \text{Cov}(Z, Y_m) = a \cdot \text{Var}(Y_m)$$

The correlation thus gets

$$\rho_{X, Y_m} = \frac{\text{Cov}(X, Y_m)}{\sqrt{\text{Var}(X) \cdot \text{Var}(Y_m)}} = \frac{a \cdot \text{Var}(Y_m)}{\sqrt{\text{Var}(X) \cdot \text{Var}(Y_m)}} = \frac{a \cdot \sqrt{\text{Var}(Y_m)}}{\sqrt{\text{Var}(X)}} = \frac{a \cdot \sqrt{\text{Var}(Y_m)}}{\sqrt{\text{Var}(X_m)}}$$

By letting  $a$  be

$$a = \rho_m \frac{\sqrt{\text{Var}(X_m)}}{\sqrt{\text{Var}(Y_m)}} \quad [\text{eq. 23}]$$

we get what we wanted, i.e.

$$\rho_{X, Y_m} = \rho_m$$

#### 4.5.1.2. Multiple dimension

It is possible to create random variables with a certain correlation also in a multi-dimension case. By generating a vector  $Z$  of zero mean, unit variance and uncorrelated random variables a new vector,  $Y$ , can be obtained with the relation

$$Y = \sqrt{C} \cdot Z + \mu \quad [\text{eq. 24}]$$

where  $C$  is the desired covariance matrix and  $\mu$  is the desired mean. To calculate  $\sqrt{C}$  it is possible to use the fact that

$$\sqrt{C} = Q \cdot \sqrt{\Lambda} \quad [\text{eq. 25}]$$

where  $\Lambda$  is a diagonal matrix of the eigenvalues of  $C$  and  $Q$  is an orthogonal matrix whose columns are the corresponding eigenvectors of  $C$ .<sup>2</sup>

If the distribution of  $Z$  is Gaussian, the distribution of  $Y$  will also be Gaussian. However, if this is not the case then the distribution of  $Y$  and  $Z$  will be different in general. The problem is to choose  $Z$  to generate a desired distribution of  $Y$ . This problem is solved by estimating  $Z$  by rearranging [eq. 24],

$$Z = C_m^{-1/2} \cdot (Y_m - \mu_m) \quad [\text{eq. 26}]$$

where the subscript  $m$  stresses that it is the measured data.

### 4.5.2. Generation of random numbers from a Gaussian distribution

Many high level programming languages have a built in uniform random number generator. However, it is common that a Gaussian random number generator is not included<sup>3</sup> [27]. To generate random numbers from a Gaussian distribution with only a uniform random number generator, it is possible to use *the Box-Muller transformation*. If  $X_1$  and  $X_2$  are independently uniform random variables, two independent Gaussian random variables with zero mean and unit variance,  $Y_1$  and  $Y_2$ , can be generated according to

$$\begin{cases} Y_1 = \sqrt{-2 \cdot \ln(X_1)} \cdot \cos(2\pi \cdot X_2) \\ Y_2 = \sqrt{-2 \cdot \ln(X_1)} \cdot \sin(2\pi \cdot X_2) \end{cases} \quad [\text{eq. 27}]$$

It is also possible to generate a Gaussian distributed random variable with arbitrary mean and variance by multiplying a desired variance,  $\sigma^2$ , with either  $Y_1$  or  $Y_2$  and adding a desired mean  $\mu$ ,

$$Z = \sqrt{\sigma^2} \cdot Y + \mu \quad [\text{eq. 28}]$$

thus making  $Z \sim N(\sigma, \mu)$ .

### 4.5.3. Monte Carlo simulations

A *Monte Carlo* simulation is a simulation technique suitable to estimate the probability of some event if an analytical approach is too difficult. By defining a sequence of Bernoulli random variables,  $X_i$ , according to

$$X_i = \begin{cases} 1 & \text{if } A \text{ occurs during the } i' \text{th experiment} \\ 0 & \text{otherwise} \end{cases}$$

<sup>2</sup> In Matlab  $\Lambda$  and  $Q$  can be generated with  $[Q, \lambda] = \text{eig}(C)$

<sup>3</sup> Matlab is an example which has a built in Gaussian random number generator

it is possible to estimate the probability of the event  $A$  by

$$\hat{p}_A = \frac{1}{n} \sum_{i=1}^n X_i \quad [\text{eq. 29}]$$

This holds if  $X_i$  is independent for all  $i$ . By letting  $n \rightarrow \infty$  the estimated probability will converge to the true probability according to the law of large numbers. Moreover, if  $n \rightarrow \infty$   $\hat{p}_A$  can be approximated as a Gaussian random variable with mean

$$E[\hat{p}_A] = p_A$$

and variance

$$\text{Var}(\hat{p}_A) = \frac{p_A(1 - p_A)}{n}$$

Since  $\hat{p}_A$  is a Gaussian distributed random variable it is also possible to create a confidence interval. If it is desired to estimate  $\hat{p}_A$  to be within  $\beta$  percent of the true value with probability  $1 - \alpha$ , then the needed number of trials is given by

$$n = \frac{\left(\frac{100c_\alpha}{\beta}\right)^2 (1 - \hat{p}_A)}{p_A} \quad [\text{eq. 30}]$$

where  $c_\alpha$  is given by the desired confidence level. Some examples of values are given in Table 1. By assuming  $\hat{p}_A$  to be small, [eq. 30] can be simplified to

$$n = \frac{\left(\frac{100c_\alpha}{\beta}\right)^2}{p_A} \quad [\text{eq. 31}]$$

Confidence level, $(1 - \alpha) \cdot 100\%$	$c_\alpha$
90%	1.64
95%	1.96
99%	2.58
99.9%	3.29
99.99%	3.89

Table 1 - Confidence Level

This requires, however,  $p_A$  to be known. If that is not the case,  $p_A$  can be estimated. By defining  $M_k$  to be a random variable representing the trial number of the  $k$ th occurrence of event  $A$ , an unbiased estimate of  $p_A$  becomes

$$\hat{p}_A = \frac{k-1}{M_k-1} \quad [\text{eq. 32}]$$

#### 4.5.4. Importance sampling

If the event  $A$  occurs very seldom, a lot of simulations have to be carried out and hence it can take a lot of time to get the desired confidence. A better approach in such a case is to use *Importance Sampling*. The basic idea is to change the distribution so the important events happen more frequently. By defining a sequence of random variables  $\mathbf{X} = (X_1, X_2, \dots, X_m)$  according to some density,  $f_{\mathbf{X}}(\mathbf{x})$ , and letting  $\eta_A(\mathbf{x})$  to be

$$\begin{cases} \eta_A(\mathbf{x}) = 1 & \text{if } \mathbf{x} \text{ is such that the event } A \text{ occurs} \\ \eta_A(\mathbf{x}) = 0 & \text{otherwise} \end{cases}$$

and letting  $\mathbf{x}^i$  be the realization of the random vector  $\mathbf{X}$  during trial  $i$ , then the *Monte Carlo* estimate defined in section 4.5.4 is

$$\hat{p}_{A,MC} = \frac{1}{n} \sum_{i=1}^n \eta_A(\mathbf{x}^i) \quad [\text{eq. 33}]$$

Instead, by generating a new sequence of random variables,  $\mathbf{Y} = (Y_1, Y_2, \dots, Y_m)$  with some other distribution,  $f_Y(\mathbf{y})$ , the importance sampling estimates gets

$$\hat{p}_{A,IS} = \frac{1}{n} \sum_{i=1}^n \frac{f_X(\mathbf{y}^i)}{f_Y(\mathbf{y}^i)} \eta_A(\mathbf{y}^i) \quad [\text{eq. 34}]$$

By choosing the density function  $f_Y$  in a clever way, less simulations will be needed and the simulation time can be reduced. To find a suitable distribution it is common to employ the so-called twisted distribution which uses concepts from large deviation theory (see e.g. [28]).

## **PART II: The mileage multiplier – step by step description**

*In this section a general description of the mileage multiplier method is described. All steps introduced in chapter 3 will be covered. This part also contains discussion and conclusions.*



## 5. The mileage multiplier

The purpose with the mileage multiplier method is to reduce the need of collecting data and still be able to verify hard demands on Collision Avoidance Systems. This is done by inserting radar targets into the collected data, re-simulate and see if the system performs an unnecessary intervention. By doing so, more situations can be created and the collected data can hence be "multiplied" by a number  $X$ , given that  $X$  times more situations are virtually created. By defining the events  $I$  and  $R$  according to

$$\begin{aligned} I &\sim \text{an unnecessary intervention occurs} \\ R &\sim \text{a false radar threat exists} \end{aligned}$$

then the probability that an unnecessary intervention will occur in a real traffic situation can be derived from Bayes' theorem, see [eq. 21]. By replacing  $A$  with  $R$  and  $B$  with  $I$ , we obtain

$$P(R|I) = P(I|R) \cdot \frac{P(R)}{P(I)} \quad [\text{eq. 35}]$$

Moreover, by assuming that  $P(R|I) = 1$  (i.e. that an unnecessary intervention always occur due to a false radar threat) and rearranging,

$$P(I) = P(I|R) \cdot P(R) \quad [\text{eq. 36}]$$

See *Step 1* and *Step 7*, described under chapter 3 and 5, of how to estimate  $P(R)$  and  $P(I|R)$  respectively. Hence, the probability that a false intervention occurs is the probability that a false intervention will occur given that a false radar threat exists times the probability that a false radar threat exists. For a definition of what a *false radar threat* is, see *Step 1* below.

The specification of requirements of the Collision Avoidance System perhaps states that the probability that an unnecessary intervention occur shall be lower than a certain probability with a certain confidence and confidence interval. This requirement might be verified with a lower amount of collected data if the mileage multiplier method is applied.

In the following subsections the different steps in the method will be presented and in most cases also be supported with an example to better illustrate that particular step.

### 5.1. Step 1: False Radar Threat Identification

The first step is to identify *false radar threats*. False radar threats are radar targets which are unharmed. For example, if the radar finds a speed bump, this radar target will be regarded as a *false threat* since this target hardly constitute a threat in reality. This chapter describes how these threats are found.

False radar targets are interesting to study since these targets might cause the system to do an unnecessary intervention if the system by mistake fuses one of these targets with a vision target, as described under section 2.3. This will happen if the state spaces of the radar target and the vision target are *sufficiently equal*. What *sufficiently equal* means in reality depends on the sensor fusion algorithm. It is important to remember that the CAS is only authorized to brake for fused targets.

To find false radar targets, a good way is to eliminate the needed vision confirmation, i.e. make the system brake for only radar targets. This modified system can then be used in a real car in live traffic in order to find situation when the systems performs unnecessary brake interventions. This is, however, not recommended since it can be very dangerous. Instead, the Collision Avoidance System should be simulated on pre-collected data. It is important that the simulated data is comprehensive in order to make sure that all types of false radar threats are identified. Therefore, if one wants the system to be robust in different environments, simulations from all parts of the world should be carried out.

The most interesting thing to examine is *when*, *why* and *how often* the radar system finds false threats. The question *how often* is easy to answer in terms of probability with [eq. 29] where  $n$  is the total number of samples analyzed and  $X_i = 1$  denotes if an false radar target are detected at sample  $i$ . For example, if 5 false radar targets are detected during 10 000 samples, then the probability of finding a false radar target is

$$\widehat{P(R)} = \frac{5}{10\,000} = 0.05\%$$

However, this is just an estimated probability. Therefore it is strongly recommended to analyze a large quantity of data, in other words let  $n \rightarrow \infty$  so that the estimated probability,  $\widehat{P(R)}$ , will converge to the true probability  $P(R)$ .

The questions *why* and *when* are more difficult to answer and it will be described in *Step 2* how this can be done. One large problem to solve in this step is the tractability problem, i.e. the problem that the simulation and post processing of the data takes a lot of time. Hence, it is not sustainable to use “standard desktop computers” but a cluster of computers<sup>4</sup> or some other kind of technique ought to be used in order to solve the problems in reasonable amount of time.

## 5.2. Step 2: Grouping and arranging the false radar threats

The second step is to group and arrange the false radar threats found from *Step 1*. This is important since the goal is later to model these targets (see *Step 4*). To be able to do this, a number of groups has to be created containing targets that behave similarly. In this work it is included to answer the question stated in *Step 1*, namely *why* and *when* the radar system finds false threats. It is, sadly, very difficult to design an algorithm to answer these two questions since it is essential to know what the environment around the host vehicle looks like. Consequently this step cannot easily be automated. Instead a manual inspection has to be carried out, and hence this step will be very time consuming. It is recommended to look at the stored video at the situations where an unnecessary intervention has occurred and try to understand why. It is also recommended to focus on the long unnecessary interventions found in *Step 1* since this situation often contains more information and are easier to analyze compared to short interventions. In addition, the driver will not notice interventions shorter than 200 *ms*, since it takes some time to build up the needed pressure in the brakes. See [24] for more information.

Each group should be uniquely described by a mathematical expression. The model has to be general enough to extract all the targets that belong to the same group. However, targets

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<sup>4</sup> A cluster is a group of linked computers, working together closely so that in many respects they form a single computer. See e.g. [http://en.wikipedia.org/wiki/Cluster\\_\(computing\)](http://en.wikipedia.org/wiki/Cluster_(computing)) for more information.



which are not included in the group should be filtered away. Targets can have a complicated and non predictive movement and these targets are more complicated to model. In such case, a number of groups can be created to cover different part of the movement of the target.

It could also be interesting to know what probability each type of target group has. This probability can be computed for each type of target and then compared to estimate the frequency of each type of target group.

### 5.2.1. Example of filter

To give an example; it is suitable to group all speed bump targets, e.g. false stationary targets, into one group since these targets will have a linear and predictive movement relative the host vehicle, given that the host vehicle is not turning. Of course there might be other types of targets acting similarly as speed bumps and hence it is suitable to place them in the same group. A suitable filter to extract these targets is given in pseudo Code Box 1.

```
for all targets do
  a = (STN >= 1);
  b = (BTN >= BTN_THRESHOLD);
  c = (stationary == true);
  d = (lateral_rate < MAX_LATERAL_RATE);

  for all samples do
    range_expected(i+1) = range_actutal(i) + range_rate(i)*SAMPLE_TIME;
    pos_error = pos_error + abs(range_actual(i+1) - range_expected(i+1))
  end;

  error_mean = pos_error / number_of_samples;
  e = (error_mean < MAX_POS_ERROR_MEAN);

  if a && b && c && d && e
    Extract_target;
  end;
end;
```

Code Box 1 – Filter Example

a and b assures that the host vehicle will “collide” with the target (and thus really is a threat) while c, d and e assures that the movement of the target relative the host vehicle is linear, logical and predictable.

### 5.3. Step 3 – Refining the groups by further Data Analysis

This step describes how the refined data collection from the different groups should be carried out. In order to create an accurate model, it is crucial to have very good knowledge of the different properties and characteristics associated with the group. Therefore, comprehensive analysis of data has to be carried out before implementing the model in any application. It is important to note that it is necessary to analyze data from every specific traffic environment where the model will be implemented. The reason for this is that different traffic environments are heavily dependent on local circumstances, such as traffic density, the quality of the roads and streets, different driving behavior and so forth.

The first step is to identify which of the parameters that needs to be analyzed. All of these variables have to be monitored and analyzed. Since it could sometimes be a complex task to

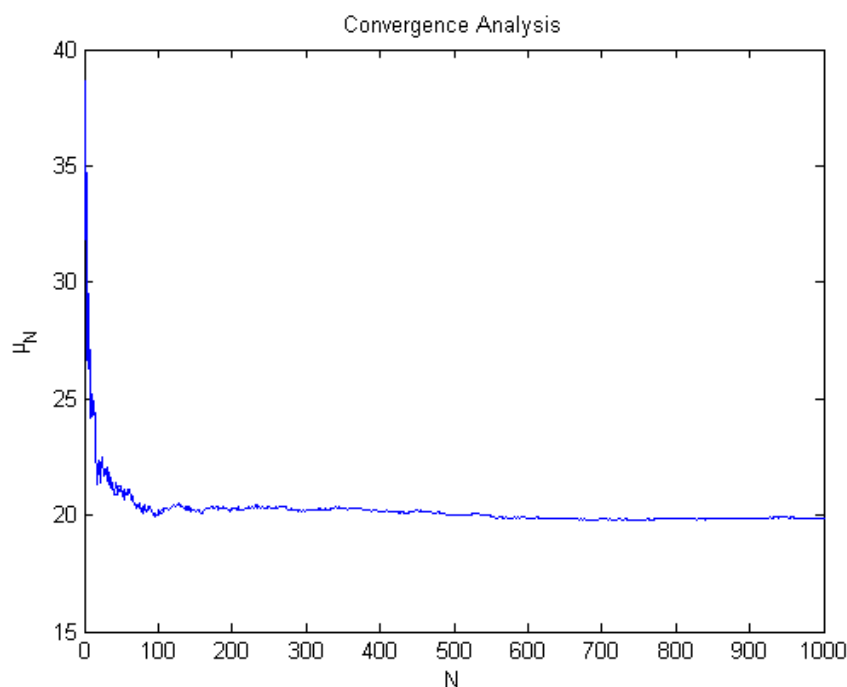
exclude any variables from the model without any change of performance, a more general approach is to model all parameters as thoroughly as possible. This is done in order not to risk the loss of any important information about the behavior of the model. The aim should always be to include as much of the collected modeling information as absolutely possible.

### 5.3.1. Convergence analysis

It is very important to collect a comprehensive amount of data to use as a base for the target parameter generation. One way of analyzing whether the collected data set is large enough is to perform a convergence analysis. This analysis consists in checking e.g. if the mean value of the data set converges towards a specific level. If that is the case, then the collected data set is most certainly large enough to provide a truthful description of the variable. The mathematical expression for the convergence analysis of the mean is given by

$$\hat{\mu}_N = \frac{1}{N} \sum_{i=1}^N x_i \quad [\text{eq. 37}]$$

where  $\hat{\mu}_N$  is the estimated mean based on  $N$  data points and  $x_i$  is the value of data point  $i$ .



**Figure 10. An example of convergence analysis. Here the variable has converged approximately after 100-200 samples**

An example is given in Figure 10. As can be seen there is a very clear convergence towards a mean value of 20 after about 100-200 samples. It is also evident that in this case the data set of less than 100 is not large enough to give a satisfying description of the variable.

### 5.3.2. Example of chosen model parameters and data

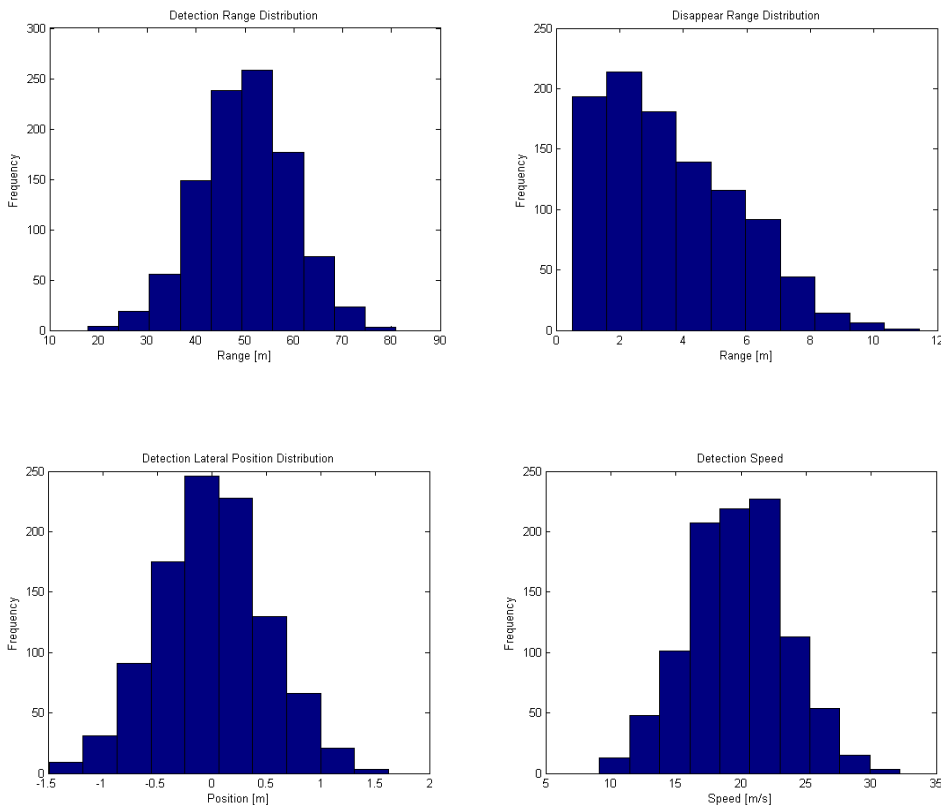
Let's return to the example in the previous step. The identified minimum number of parameters considered to be necessary for a realistic modeling of the group specified in the previous step is:

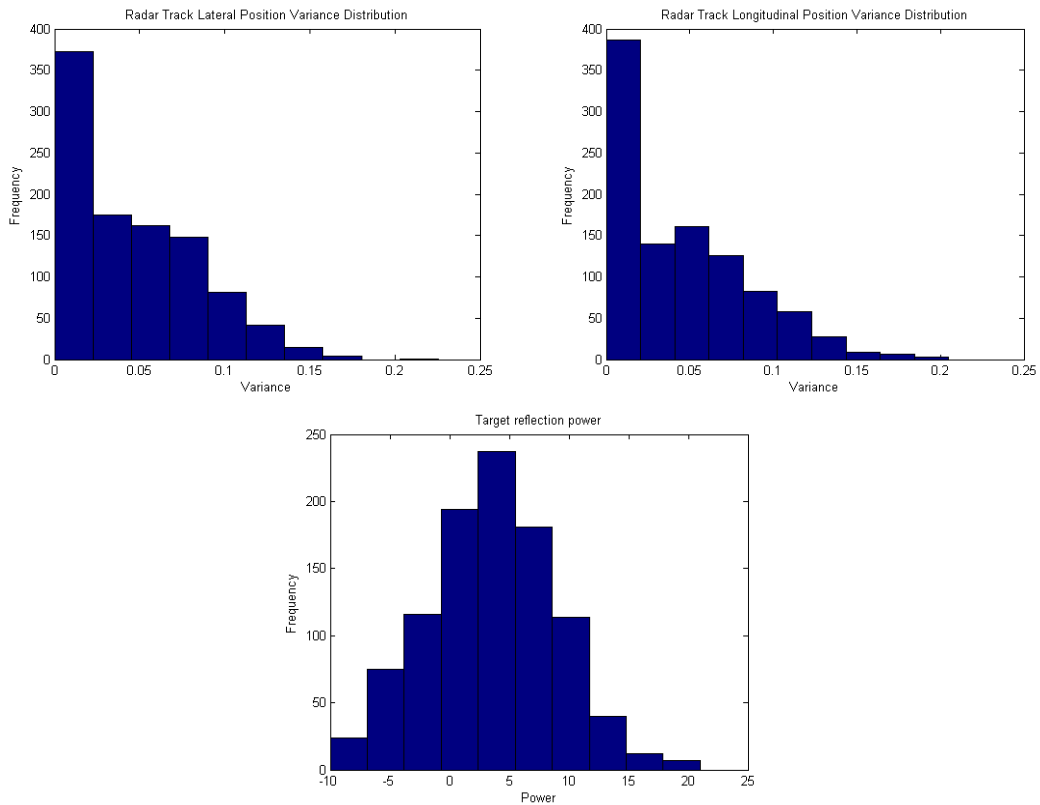
- Radar detection range ( $m$ )
- Radar disappear range ( $m$ )
- Radar mode flag (*Long Range, Mid Range*)
- Lateral position of detection ( $m$ )
- Target width ( $m$ )
- Target reflection strength ( $dB$ )
- Moveability status flag (*Fast Moveable, Slow Moveable, Static*)
- Host vehicle detection speed ( $m/s$ )
- Fluctuations of target tracking position (*longitudinal, lateral*) ( $m$ )
- Target appearance frequency (*Number of detections per Covered Distance*)

The list of the parameters considered to be of high importance for the actual target modeling will of course vary depending on how the system is designed. Therefore, the above specified parameters should be seen as a general example on how a collection of important modeling variables could be assembled.

### 5.3.3. Example of data

Data was generated in a random fashion in order to illustrate the method better. This data will later be used in examples in the proceeding steps. Assume that 1000 targets were extracted with a parameter distribution defined in the following figures:





**Figure 11 – Example of distribution of some important parameters**

The target width is assumed to be 0 m for all identified targets and binary flags are set true according to

- Fast moveable: 52%
- Slow moveable: 0%
- Static: 100%
- Long Range Lobe: 98%
- Mid Range Lobe: 98%

### 5.3.4. Example of convergence analysis

Figure 12 shows a plot over the convergence of the mean of the variables generated above. Some of the curves are on top of each other and thus difficult to see, though the important part in the plot is to notice that all variables have converged. The last variable to converge is the *Detection Range* which needs around 200 data points in order to do so. The convergence criterion consists of visual inspection.

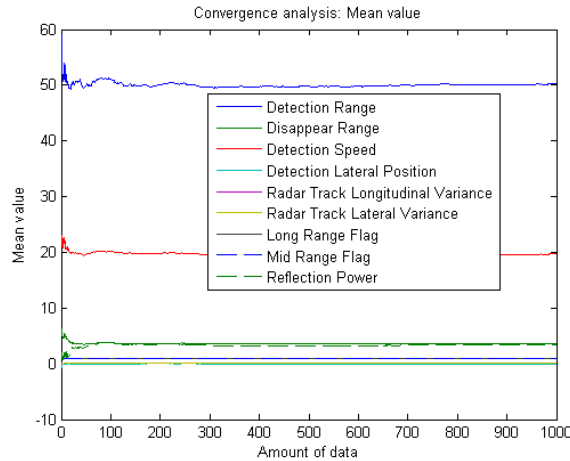
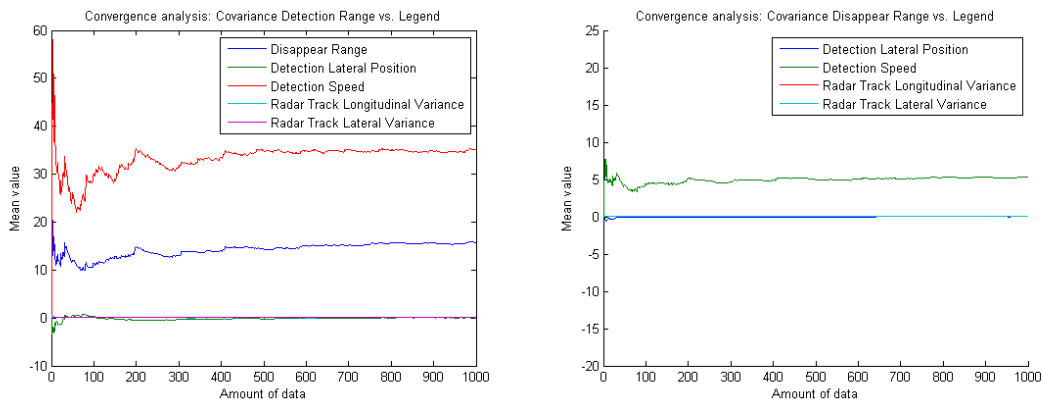
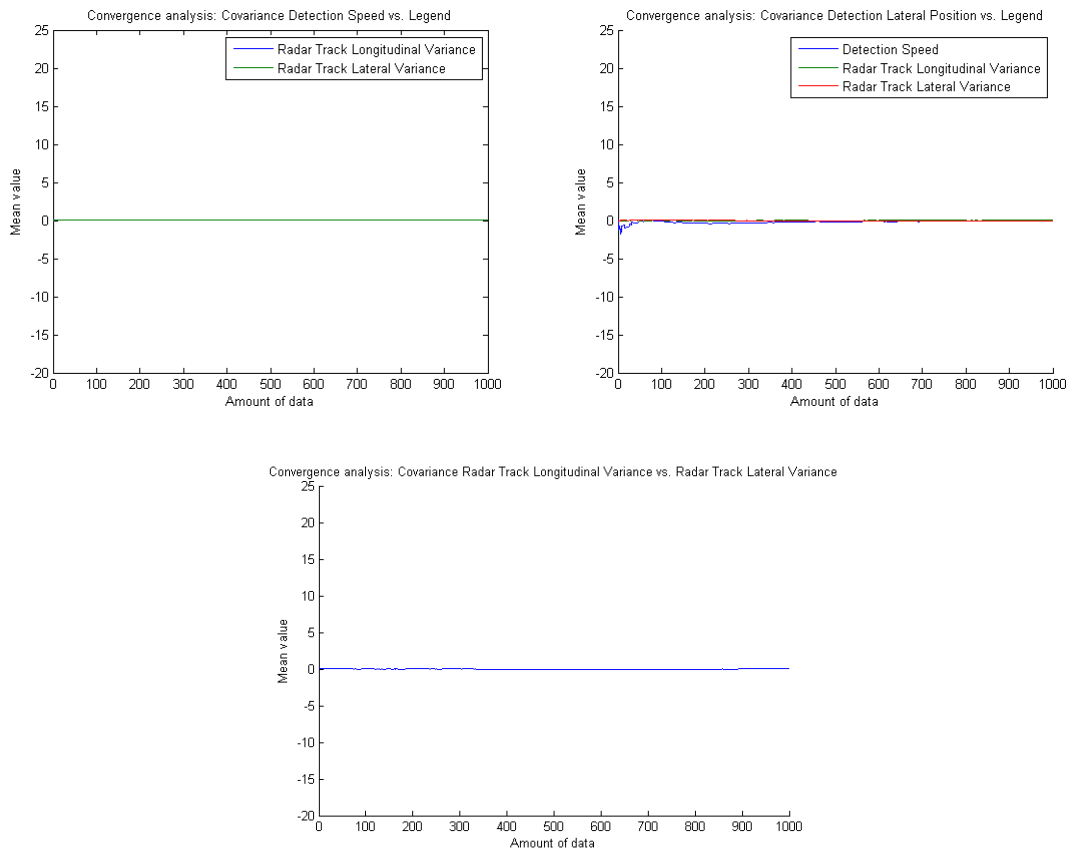


Figure 12 – Convergence analysis of the mean value. All variables have converged.

The Figure 13 shows the convergence analysis of the covariance between selected variables. It is obvious that all covariance have converged as well. If the distributions are Gaussian this is the only convergence analysis needed. If not, moments of higher order will need to be analyzed as well. However, here the analysis is limited to lower order since it is enough to illustrate the method.





**Figure 13 – Convergence analysis of the Covariance. All Covariances have converged.**

## 5.4. Step 4: Creating the Models

The model of the targets can be formed in many ways. One way is to use the extracted targets as they are. This approach will, however, only capture the cases which are observed. To be more general, a better way is probably to form *statistical models*. By doing this, all possible combinations of targets can be created, even those not (yet) observed. A weakness with this approach is that unrealistic targets might be created which cannot occur in reality. One must therefore be careful when using this approach and make sure that the targets really are physically possible. The host vehicle and stationary targets can be modeled as described in the theory section.

It is also essential to model all important relations between the different variables. The linear relation can be modeled by [eq. 22] or [eq. 24]. It is nice when the distributions can be approximated as Gaussian since it is e.g. easy to draw a value from this distribution. However, there is a possibility that some of the distributions cannot be approximated as Gaussian. To draw a value from these distributions the technique described below can be used. In addition, there might also exist non-linear relations between the variables which might be interesting to analyze as well. How this can be done is though not described in this thesis.

### 5.4.1. Draw values from a distribution

The results obtained during simulation and analysis of traffic data have shown that one method for generating the model parameters could be to use a probabilistic approach, where the measurement data is organized using different distributions. This method can be used for

producing values for several of the modeling parameters such as *Detection Range*, *Disappear Range* and *Target Reflection Strength*. As an example of how the method could be used, let us first denote that the data set which is plotted in Figure 14 shows the radar detection ranges of a specific test run. In this case the detection range in meters vary between a maximum value of  $R_{max}$  and a minimum value of  $R_{min}$ . It is then possible to divide the total set of data into a number of  $N + 1$  subsections where

$$R_{min} \leq R_i \leq R_{max}$$

$$i = 1, 2 \dots N$$

where  $R_i$  is the value of detection range assigned from the distribution, and where the constant

$$N \in \mathbb{Z}^+$$

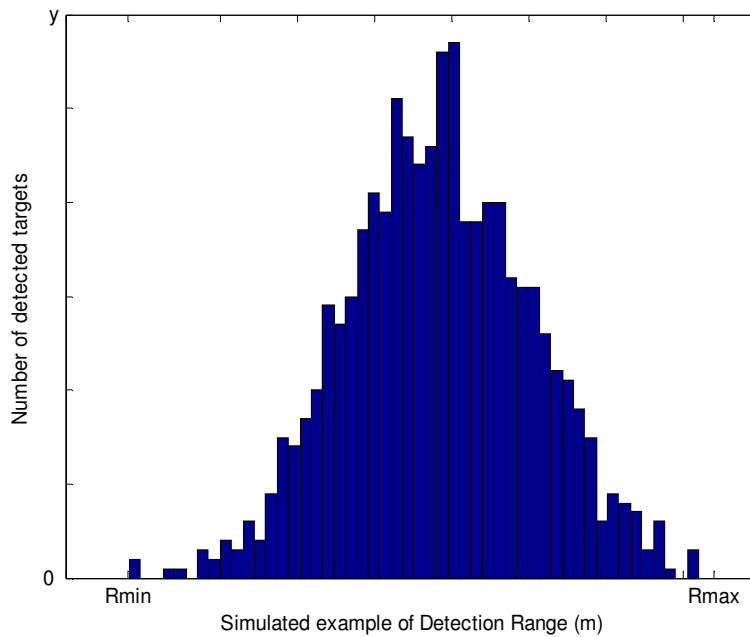
Let us say that a variable  $x$  should be set to a randomly picked value from the specified detection range data set. All probabilities is then normalized so that the total sum of probabilities becomes

$$\sum_{i=1}^N P(R_i) = 1$$

where  $P(R_i)$  indicates the probability for each of the target detection ranges  $R_i$  to be randomly picked.

Now, since the probability for all of the different values of detection range is known, it is possible to assign the variable  $x$  using this known distribution together with a uniformly distributed random variable ranging between one and zero. This random variable could then be used to choose which value of detection range  $R_i$  to assign to the created modeling variable  $x$  according to the set of probabilities connected to the data set.

By using a large number of subsections  $N$ , it is possible to reach high resolution of the detection range. However, analyses applied to very large data sets might result in substantial amounts of detected radar targets of the specified type. Hence, it might be useful to choose the number of  $N$  while carefully considering limitations due to computational time and capacity.



**Figure 14 - Example of data distribution used for randomly picking a variable of Detection Range used for target modelling.**

In the code box below a pseudo-code example is given of how to draw a value from an arbitrary distribution. In the pseudo-code *Detection Range* has been used as an example but the code is general.

```

randomNumber = GenerateUniformRandNumber; %Generate unif. distributed %random
number between 0 and 1
detectionRange = 0;
rangeProbability = 0;
counter = 0;

%Create table of size N containing probability for each subsection.
probabilityTable = [0.01 0.09 0.10 0.12 ... ];

%Create table of size N containing the different detection ranges (in meters)
specificRange = [1 2 3 4 ... ];

while (detectionRange == 0) do

    rangeProbability = rangeProbability + probabilityTable(counter);

    if randomNumber less than rangeProbability
        detectionRange = specificRange(counter);
    end;
    counter = counter + 1;

end;

```

**Code Box 2 - Draw a value from distribution.**



### 5.4.2. Example of Model

Let's assume that we want to create a statistical model based on the example of collected data in the previous step. Moreover, assume that a correlation have been observed between the parameters specified in the vector  $\mathbf{X}$  below.

$$\mathbf{X} = \begin{bmatrix} \textit{Detection Range} \\ \textit{Disappear Range} \\ \textit{Detection Speed} \\ \textit{Detection Lateral Position} \\ \textit{Radar Track Longitudinal Variance} \\ \textit{Radar Track Lateral Variance} \end{bmatrix}$$

By using [eq. 24] it is possible to model this correlation by first calculating the covariance matrix. In this example the covariance matrix is found to be

$$C = COV[X, X] = E(X - E[X]) \cdot E(X - E[X])^T =$$

$$= \begin{bmatrix} 99.793 & 15.987 & 33.831 & -0.0106 & 0.0809 & 0.0329 \\ 15.987 & 4.6677 & 5.4077 & -0.0141 & 0.0121 & 0.0091 \\ 33.831 & 5.4077 & 15.510 & -0.0213 & 0.0293 & 0.0133 \\ -0.0106 & -0.0141 & -0.0213 & 0.2509 & -0.0006 & 0.0004 \\ 0.0809 & 0.0121 & 0.0293 & -0.0006 & 0.0017 & 0.0001 \\ 0.0329 & 0.0091 & 0.0133 & 0.0004 & 0.0001 & 0.0016 \end{bmatrix}$$

$\sqrt{C}$  can then be computed with [eq. 25] where  $\Lambda$  and  $Q$  is

$$\Lambda = \begin{bmatrix} 114 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3.69 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2.04 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.250 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.002 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.002 \end{bmatrix}$$

$$Q = \begin{bmatrix} -0.932 & -0.266 & 0.186 & -0.0217 & 0.001 & 0.001 \\ -0.1513 & -0.322 & -0.9798 & 0.018 & -0.002 & 0.001 \\ -0.328 & 0.909 & -0.073 & 0.056 & 0.000 & 0.001 \\ 0.000 & -0.004 & 0.008 & 0.998 & -0.003 & -0.001 \\ -0.001 & 0.000 & 0.001 & -0.002 & -0.579 & -0.815 \\ 0.000 & 0.000 & -0.002 & 0.002 & 0.816 & -0.579 \end{bmatrix}$$

Since some of the parameters cannot be approximated as Gaussian,  $Z$  has to be determined according to [eq. 26]. Hence, by drawing a value of  $Z$  according to Code Box 2 and then use [eq. 24],  $Y$  will be created with the correct distributions and correlation between the parameters.

### 5.5. Step 5 – Applying the Models

It is now time to insert the modeled radar targets into the system and thus creating the new modified traffic data. The targets are inserted according to Figure 15. This can be done in numerous ways. A first good approach is to use a *Monte Carlo* approach, as described in

Section 4.5.3. If it turns out that this approach results in too many required simulations (see *Step 7*), then Importance sampling could be used instead, see section 4.5.4. It is thus required to identify parameters which are more likely to trigger an unnecessary intervention. This can of course be tricky especially if the sensor fusion and the threat assessment is unknown. However, from *Step 1-3* there might be some guidance what parameters are important to triggering the system. Otherwise "trial and error" iterations can be carried out to figure out what parameters are important.

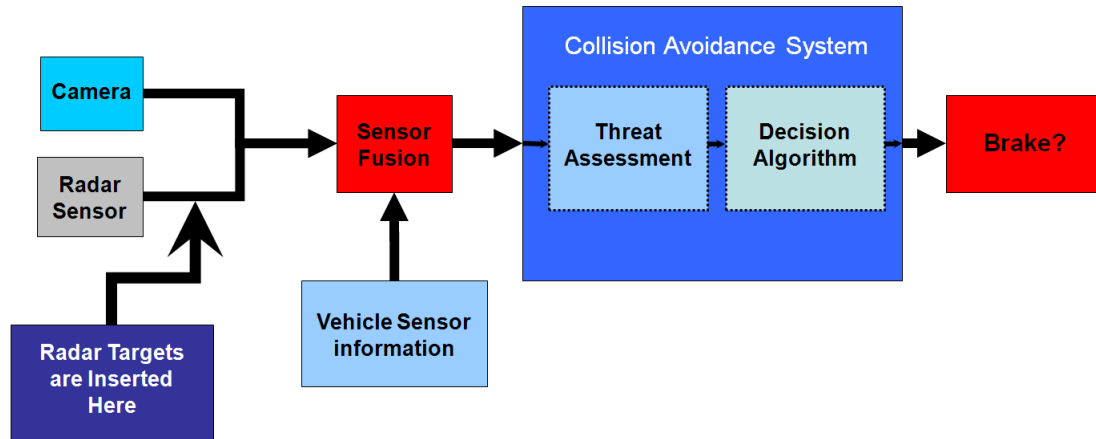


Figure 15 – Inserting False Radar Targets into the Collision Avoidance System

### 5.5.1. Example of importance sampling

As an example, let say that one specific binary flag parameter has been observed to be important for the system to trigger an invention. Assume that this parameter is altered to be set as true 100% of the time, though in reality this flag is only true in 10% of the cases. Equation [eq. 34] thus gets

$$\hat{p}_{A,IS} = \frac{1}{n} \sum_{i=1}^n \frac{0.1}{1} \eta_A(\mathbf{y}^i) \quad [\text{eq. 38}]$$

Let's assume that  $A$  occurs 10 times more often with the new distribution. If 100 targets are inserted and an intervention is observed 1 time, then  $\hat{p}_{A,IS} = 0.1\%$ . This can be compared to the *Monte Carlo* approach which hence would need 1000 targets to be inserted in order to get 1 observation. Only considering some of the targets (i.e the targets that constitute a threat) can also be seen as a kind of importance sampling.

### 5.6. Step 6 – Simulation of Collision Avoidance System

Since it is difficult and dangerous to test the system with virtually inserted targets in reality, the system should be simulated in order to analyze the Collision Avoidance System. The system is simulated with the mixed data containing the original and inserted radar targets. Everything after the insertion point has to be simulated in order to study the system behavior. There are a lot of simulation programs on the market, more or less suitable to simulate a system like this. A very good alternative is Simulink which is an extension of MATLAB. If the Collision Avoidance System is not implemented in a simulation tool, this of course has to be done first.

## 5.7. Step 7 – Perform Analysis and Draw Conclusions

A very important step is to analyze the results from the simulations and to draw conclusions. How many times did an unnecessary intervention occur and how many targets were analyzed?

Let's take an example based on the data defined in *Step 3*. Define  $R$  to be the event that a false radar target exists and  $I$  to be the event that unnecessary intervention occurs, as was done in the beginning of this chapter. Assume that we observe 2 false targets during 144 000 samples, thus making the probability that a certain target occur in a real traffic

$$\widehat{P(R)} = \frac{2}{144\,000} = 0.0014\%$$

Let's also assume that the system performed 5 unnecessary interventions with 100 000 inserted targets. Again, the estimated probability of an unnecessary intervention is

$$\widehat{P(I|R)} = \frac{5}{100\,000} = 0.005\%$$

By equation [eq. 36] the probability that the system will perform an unnecessary intervention during a specific sample in reality is

$$\widehat{P(I)} = \widehat{P(R)} \cdot \widehat{P(I|R)} = 0.00005 \cdot 0.000014 = 7 \cdot 10^{-8}\%$$

If the sample time is 0.05 [s], then the probability that the system will perform a unnecessary intervention during a specific hour is  $7 \cdot 10^{-8} \cdot 20 \cdot 3600 = 5.04 \cdot 10^{-5}\%$ . If it is desired to know that this estimated probability to lie within 25% of this estimate with a confidence of 95% it is, by [eq. 31] it is needed to analyze

$$n = \frac{\left(\frac{100 \cdot 1.96}{25}\right)^2}{5.04 \cdot 10^{-7}} = 1.22 \cdot 10^8$$

number of hours. Since, in this example, a target occur 1 time per hour it would be equivalent to insert  $1.22 \cdot 10^8$  targets instead. This will of course not be possible if only using “standard desktop computers”. Even a cluster of computers could have problems with this amount of hours needed to be analyzed. Either a weaker confidence could be applied or an increase in  $P(R)$  and/or  $P(I)$  (by e.g. importance sampling) would decrease the needed amount of simulations.

## 5.8. Step 8 – Summarize and Take Decisions

Are the results acceptable or is there a reason to believe that the models used are not detailed enough? Has enough simulation been carried out to be able to create a desired confidence interval with desired confidence? Are the (statistical) models based on sufficiently collected data? These questions are essential when the simulations are done. If the simulations show that the requirement of specification is not met, it could be interesting to test the simulated scenarios in reality to verify that these situations can constitute a problem in reality.

In the example it is obvious that more simulations have to be carried out if it is desired to construct a confidence interval. Since the convergence analysis in *Step 3* showed that the amount of collected data is enough, a suitable step to return to is *Step 4* (see Figure 8) and perhaps tune some of the parameters. In addition, it could be suitable to use the importance sampling approach in this second iteration in order to reduce the number of needed targets to be inserted.

### **5.9.Step 9 – State the final results and evaluate**

When satisfied with the results from the simulations it is possible to know whether the system does fulfill the system requirements or not. If the system does not fulfill them, perhaps the sensor fusion algorithm or the threat assessment algorithm must be tuned in order for the system to perform better. With the new system it is possible to once again use this method to verify that this new system is working properly. If the simulation does show that the requirements are met, one could be confident in the system. However, it is important to realize that this method is built on models and simulations which never can capture the reality to 100%. Moreover, if a weak spot of the Collision Avoidance System is found, it is recommended to perform real life trials in order to determine if the weakness is a problem in reality.

## 6. Discussion

When collecting data for target generation it is very important to be aware of the difficulties that the choice of collection might cause. Ideally the data collection will be infinitely large, but since one of the main objectives with the method is to reduce the collection of data it is of course not possible. The convergence analysis presented in the method should serve as a good support to know whether the data collection is sufficient.

Another very important aspect to consider is if the collected target data is applied to a relevant data set. This means that it is very important to consider if the generated radar targets have sufficient relevance in the actual traffic environment that they are applied to. For example, if target data is only collected during freeway driving at a high speed on Autobahn, it might not have very high relevance for a situation with heavy traffic jam at low speed in Tokyo. It could hence be risky to place targets in environments where data has not been gathered and this is thus not recommended. The optimal way of using the collected data is possibly to re-apply the radar targets into the exact same environment that it was originally collected from thus ensuring that the multiplied targets will have a very high degree of relevance.

To be able to use this method efficiently a lot of computer capacity is needed, especially to process the data but also a large storing space is needed. With the “standard desktop computers” used by the authors to test the method, it took about 30-60 minutes to insert about 100 virtual targets and simulate five minutes of the system and do some post processing.

If a statistical approach is used, as was done in the example, it is important to consider that targets might be created which are not physically possible. For example, during our simulation it could happen that the Disappear Range was larger than the Detection Range. To deal with this, these targets were discarded and new ones were created. A better way of handling this would perhaps be to change the model such that these cases cannot occur. It is also important to know to what extent the inserted targets constitute a threat to the system. It is possible to insert targets which disappear before the host vehicle has come so close that the target constitutes a threat. Ideally, all inserted targets will constitute a threat, but during simulation it was found that some targets disappeared too far away. To compensate for this, these targets were not counted, but perhaps a better approach would once again be to modify the model so these situations do not occur.

The results showed that a lot of hours need to be simulated in order to get a strong confidence that the estimated probability really is close to the real probability. Exactly what the system requirement states about unnecessary intervention is not known to the authors. However, since there already exists Collision Avoidance Systems, verified with real traffic data collection, this must mean that this system must be able to be verified faster with simulations, assuming that the processing capacity is high.

It must also be stressed that the results from the simulation must be regarded with caution. As already mentioned, this method is based on models and simulations which never can capture the reality to 100%. It is thus recommended to view the result from this method as a *complement* to the real traffic analyses.

This method should also be viewed as a first step towards a more sophisticated method. As mentioned, there might be better ways of modeling the targets as well as applying them. For example, it might be unnecessary to place radar targets in environment where no car exists since the probability that the system will fuse a radar target with a vision target is extremely small. In addition, no time have been spent of analyzing when the camera system finds *false vision threats*. This could also be interesting to analyze.

## 7. Conclusion

The mileage multiplier method has potential to be a very valuable verification tool of Collision Avoidance Systems with the purpose of reducing the need of data collection. It should preferably be used as a complement to real traffic analyzes, rather than a stand-alone verification tool. It is important that the models of the targets used together with this method reflect the reality – otherwise the results from this method are not valid. In this thesis a statistical approach has been suggested to model the targets, but there exists other methods. It has also been suggested to use a *Monte Carlo* simulation or *Importance Sampling* but other techniques exist as well. The focus has been on the radar targets, and more analyses of the vision system ought to be carried out.





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